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Low-Power Design and Critical Event-Triggered Transmission Scheme for Wireless Strain Gauge Sensor Node in Aircraft Structural Health Monitoring

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Abstract: The development of wireless sensor network integrated into aircraft structural health monitoring (SHM) can help to achieve the goal of deploying more sensors for the significant benefits in flexibility, interoperability, mass reduction, system redundancy and enhanced robustness. The objective of this paper is research and development concerning wireless strain gauge sensor node mounted on aircraft, towards prolonging the battery lifetime and balancing the power-performance tradeoff. This wireless sensor node can acquire the strain in a structure, convert, conditioning, process and finally transmit data by wireless connection. This wireless sensor node included mainly a nonlinear bridge strain transducer, bridge sensor conditioner, lookup table, low pass filter, ADC, MCU, low-power RF transceiver, external memory, RTC, energy harvesting, energy storage and management. The functions, considerations and specifications of these main parts were described. A low-power design and a critical event-triggered transmission scheme were illustrated and applied to reduce power consumption and conserve network bandwidth. The experimental results show that this wireless strain gauge sensor node is reasonable potential for aircraft SHM. *Copyright © 2013 IFSA.*

Keywords: Aircraft structural health monitoring, Wireless strain gauge sensor, ZigBee, Energy management.

1. Introduction

Structural health monitoring (SHM) is the process of detecting and interpreting any "changes" in a structure, especially for adverse phenomenon. The goal of SHM is to improve the safety and reliability, and reduce life-cycle costs in civil and military infrastructures by detecting damage before they reach a critical status. To achieve this goal, the relevant technology is being developed to transit from qualitative visual inspections and schedule-based maintenance procedures to more quantifiable and automated damage assessment processes. These processes are implemented by using both hardware and software with the intent of achieving more effective condition-based maintenance (CBM). The extensive technology based on SHM has been developed over the last 20 years [1]. A living example of this technology is embedding sensors in engineering structures such as bridge [2,3], where the distributed sensors acquire various real-time structural changes like stress and strain, and then transmit them to a remote data acquisition centre for monitoring and evaluation. As a result, more information needs to be moved somewhere, so that the only hope for the traditional hard-wired method may not be an optimum result, especially for some special situations.

The wireless sensor network (WSN) will be a most promising technology to replace bulky cables and fixed wiring. Today, WSN is used in many industrial and consumer applications, such as structural health monitoring, industrial process monitoring and control [4], consumer electronics [5] and so on [6, 7]. Moreover, the development of WSN is motivated by military applications such as battlefield surveillance [8, 9]. Wireless communication can remove the cabling problem of the traditional monitoring system and considerably reduce the maintenance cost. Compared to a hard-wired sensor network, WSN has double or even quadruple redundancy in the size of sensor hardware and wire harnesses [10]. With the aid of modern technology, the real-time monitoring based on WSN becomes possible. As a result, WSN can bring many special favors for SHM.

To select a suitable communication protocol standard is a key to the interoperable issue of WSN. ZigBee is a suite of high level wireless communication protocols based on an IEEE 802.15.4 standard. ZigBee is targeted at the applications that require a low data rate, long battery lifetime, secure networking and supporting up to 255 nodes per network, therefore it is particularly suitable for WSN [11, 12]. ZigBee Devices can self-organize into a short-range wireless communication network to support relatively low throughput applications such as distributed sensing and monitoring [13, 14]. ZigBee network ranges from simple single-hop star topologies to more complex multi-hop mesh networks. Although ZigBee technology is currently still developing and costly in a certain extent, the emergence of ZigBee standardization is appealing because its potential is closely related to the objectives for relatively fast, low cost and simplified implementations compared to more traditional wired network installations applied in WSN.

2. Aircraft Structural Health Monitoring

Several studies have been conducted to develop SHM which use the data collected from distributed wireless sensors embedded into the structure [15, 16]. Although the WSN used in SHM has been developed for many years, the most examples are for the fixed building or workplace. The researches on vehicle and aircraft are only just beginning, whereas many problems still need to be addressed. With the increasing use of novel materials and sophisticated equipments in aircraft structures, it is necessary to develop an innovative method for structural safety assessment. For example, composite structures and metal structures constitute almost the bodies of the aircraft. Most failures of the laminated composite structures originate in the repeated cyclic stresses and impacts to form delamination. Most failures of the fabricated metal structures originate in the development of corrosion and fatigue with the passage of time. For these cases, visual inspection is not a reliable method for failure detection. Moreover, the widely used schedule-based maintenance procedures have a high cost [10]. The development of an integrated SHM and reporting system for pitch links on a helicopter had been described in [17].

Our previous works are to develop and evaluate a versatile aircraft SHM system installed for a certain unmanned aerial vehicle (UAV). SHM system has capable of synchronized monitoring data from a range of wireless sensors cooperated with some hard-wired sensors. The wireless sensors typically are low-power level or passive devices, including strain gauges, accelerometers and thermocouples, etc. In contrast, the hard-wired sensors typically are relatively high power level or high sampling rate devices, including gyroscopes, magnetometers and GPS, etc.

Fig. 1 shows the approximate deployment of several representative devices required for aircraft SHM system. These wireless devices create a mesh network based on ZigBee protocol. The wireless sensor nodes are located spatially on engine, wing, rudder and other critical structural elements to acquire information about the aircraft status. Combining a single personal area network (PAN) coordinator, some ZigBee routers with various wireless sensor nodes are a typical WSN. The sensor node (generally reduced dunction device, RFD) may be tiny, simple device with a very limited power consumption, which has only sufficient functionality to talk with its parent device but cannot relay. ZigBee Router (full function device, FFD) acts as an intermediate node to relay data from other devices, which can gain an additional communication link to extend distance and reliability. PAN coordinator known as central gateway can originally establish and configure the network, which is the most capable of the three node types but exactly one coordinator in each network [13]. Once the aircraft status happens to change, the vibration, pressure, temperature and other characteristic signals will carry a wealth of information. These distributed wireless sensor nodes have access to the response to changes in physical parameters on critical area, then process and transmit the data from child nodes via their parent routers to only PAN coordinator. PAN coordinator provides a wired connection to the data aggregator which implements collect, process, analyze, storage and eventually present available information to the operator.

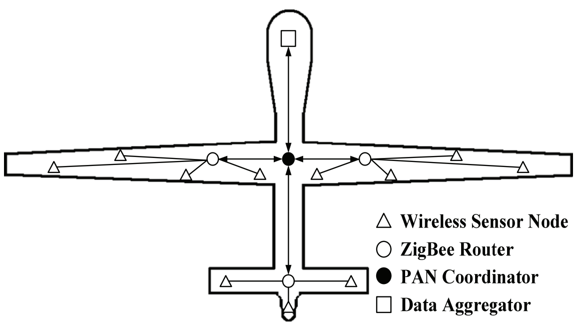

Fig. 1. The WSN Approximate Deployment for Aircraft SHM System.

3. Hardware Descriptions

Generally speaking, a wireless sensor node includes the following main parts: signal acquisition, signal conditioning, MCU, external memory, RF transceiver and power source. Power source contains energy storage, power supply and an option of energy harvesting. Fig. 2 shows a modular design approach that provides a flexible and versatile platform to address the needs of various applications. Signal acquisition is the processes of sampling signals that measure and convert physical parameters into electrical signals. Signal conditioning regulates and filters the resulting samples into a form that can be converted to digital values. The MCU performs tasks, processes data and controls the functionality of other components in the node, such as executing communication protocol and running local computation algorithms. External memory uses for storing application related and programming the device. RF transceiver is an essential component of wireless communication to transmit and receive RF signals. Power supply provides electronic components with stable and sustained electric powers extracting from energy storage including the usual form of either a battery or a capacitor. Energy harvesting generates electric powers from ambient energy source and renews energy storage. The functions, considerations and specifications of these main parts used in our demonstration are described as follows.

Strain gauge sensors are the most common devices for the electrical measurement of structural deformation in aircraft. Strain gauge sensors can be used to measure the fatigue loading experienced under various conditions of speed, weight and mission configuration more accurately far better than the older, less accurate counting accelerometer methods. These strain gauge sensors can be embedded into the composite structures or attached to the metal surfaces to more accurately monitor for potential fatigue damage induced by thousands of flight hours, high stress maneuvers and landings.

3.1. Signal Acquisition and Conditioning

3.1.1. Nonlinear Bridge Strain Transducer

A strain gauge (also known as strain gage) is a component used to measure the strain of an object. The bonded metal foil strain gauges are a mature technology used for many situations. The typical foil resistive-type gauge consists of a wire grid network embedded on an elastic layer, which is bonded with an epoxy layer onto the object of interest. When the object occurs to deform under load, the deformation is transferred to the wire network, causing resistive changes in the material. Since the changes in the resistive characteristics of metallic foil gauges to applied strain are very small, so signal processing is required to convert these changes into voltages that are detectable and able to be further processed. One of the most popular detection circuits is the Wheatstone bridge. The Wheatstone bridge can be either a quarter bridge or a half bridge, a full bridge. The quarter bridge has only one active arm, i.e. strain gauge, and it is the simplest form of Wheatstone bridge configuration. The quarter bridge is shown in Fig. 3 and used in our demonstration.

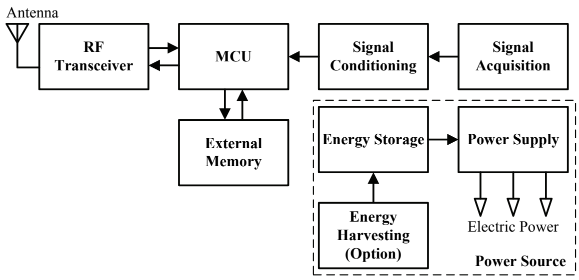

Fig. 2. The Typical Architecture of Wireless Sensor Node with Single-Channel Sampling.

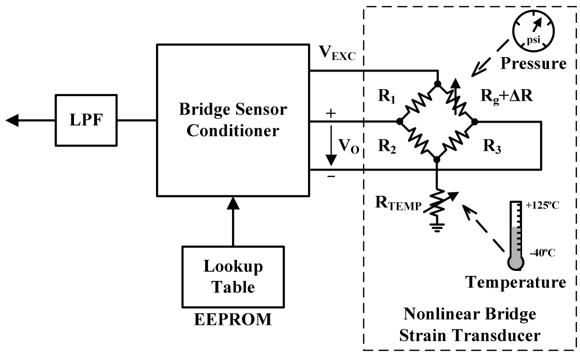

Fig. 3. Signal Acquisition and Signal Conditioning.

A fundamental parameter of the strain gauge is its sensitivity to strain, expressed quantitatively as the gauge factor (GF). Gauge factor is defined as the ratio of fractional change in electrical resistance to the fractional change in strain length:

$$GF = \frac{\Delta R / R_g}{\Delta L / L} = \frac{\Delta R / R_g}{\varepsilon}, \quad (1)$$

where ε is the axial strain, L is the nominal length and R_g is the equivalent resistance of the strain gauge. ΔL and ΔR are respectively the change in the length and resistance due to applied strain. A detailed treatment on stress-strain relationship of strain gauge can be found in [18]. When an excitation voltage, V_{EXC}, is applied across the bridge, the output voltage of the bridge, V_O will be equal to:

$$V_O = \left(\frac{R_2}{R_1 + R_2} - \frac{R_3}{R_3 + R_g} \right) V_{EXC} \quad (2)$$

In the absence of strain, it is apparent that when $R_1 = R_2$ and $R_3 = R_g$, the bridge is said to be balanced and its output is zero. When strain is applied to the strain gauge, R_g is changed by a small amount, ΔR, this will result in an unbalance of bridge and produce a nonzero output voltage. The bridge equation above can be rewritten to express V_O/V_{EXC} as a function of strain:

$$\frac{V_O}{V_{EXC}} = \left(\frac{R_2}{R_1+R_2} - \frac{R_3}{R_3+R_g+\Delta R}\right) = \frac{GF\cdot\varepsilon}{4}\left(\frac{1}{1+GF\cdot\frac{\varepsilon}{2}}\right) \quad (3)$$

The bridge excitation voltage, $V_{EXC,}$ affects both the output sensitivity and the gauge self-heating. From a measurement standpoint, a higher excitation voltage level is desirable, but a lower voltage level can reduce gauge self-heating. The electric power in the gauge is dissipated as heat which must be transferred from the gauge to the surroundings. The gauge temperature is therefore a function of the ambient temperature and the temperature rises due to high power dissipation [19]. Assuming that all nominal resistances exactly equal, I_g is the gauge current, P_g is the gauge power dissipation and given by the following equation:

$$P_g = \frac{1}{2}\times\frac{V_{EXC}{}^2}{R_3+R_g} = \frac{V_{EXC}{}^2}{4R_g} = I_g{}^2 R_g \quad (4)$$

Table 1 illustrates the relationship between gauge resistance and power dissipation under different excitation voltages. It is worth noting that reducing the excitation voltage or increasing the gauge resistance will lower power dissipation, whereas an over-adjustment will cause an insensitive detection. Moreover, increasing some the non-gauge resistance values of R_1 and R_2 is also a good way to further lower the total power consumption.

Table 1. Gauge Power Dissipation in a Quarter Wheatstone Bridge.

Resistance (Ω) / Power Dissipation (mW) / Excitation Voltage (V)	1000	500	350	120
0.1	0.0025	0.005	0.007	0.021
0.2	0.010	0.020	0.029	0.083
0.5	0.0625	0.125	0.179	0.521
1.0	0.250	0.500	0.714	2.083
2.0	1.000	2.000	2.857	8.333
3.0	2.250	4.500	6.429	18.750
4.0	4.000	8.000	11.429	33.333
5.0	6.250	12.500	17.857	52.083
10.0	25.000	50.000	71.400	208.300

In our demonstration, the nominal values are: $R_1 = R_2 = 3000\ \Omega$; $R_3 = R_g = 350\ \Omega$; $V_{EXC} = 2.0$ V. The total equivalent resistance of this Wheatstone bridge is about 626.866 Ω. Since the change value of R_g (ΔR) is very small (only single-digit Ohm), the power consumption between full load and empty load is not significantly different. Hence the gauge power dissipation is about 2.857 mW and the total bridge power consumption is about 6.381 mW.

3.1.2. Bridge Sensor Conditioner

As illustrated in the above section, the output voltage from the Wheatstone bridge is very small and cannot be increased more by some changes in the circuit configuration. Hence, the amplification of the bridge output voltage is required so that it can be further processed. Since the presence of the 1/(1+GF•ε/2) term in equation (3) that indicates the nonlinearity of the quarter-bridge output with respect to applied strain, in addition, temperature factor also makes a serious impact on the output response [20]. Therefore, the appropriate calibration and compensation are required to perform. Analog processing or digital processing is the common way to convert and linearize the sensor sampling signal, but a highly integrated solution is often more fast, precise and even energy-efficient. Compared to a simple operational amplifier, a programmable gain amplifier (PGA) has more advantages, including adjustable Programmable Gain, Programmable Offset, Update of Calibration, Temperature Compensation, Over-Scale and Under-Scale Limits. These feathers are more suitable for connection to nonlinear bridge strain transducer. The PGA309 is a programmable analog signal conditioner designed especially for nonlinear bridge strain transducer, it may perform necessary functions to calibrate, compensate for temperature variance, scale and linearize the sensor signal [21]. Up to 17 temperature coefficients are stored in external EEPROM to allow a linear interpolation algorithm for a piecewise linear temperature compensation. These temperature coefficients are measured in our laboratory over −40 °C to 125 °C.

The PGA309 draws a quiescent current including from analog voltage supply (SA) and digital voltage supply (SD). Its typical value ($I_{SA} + I_{SD}$) is 1.2 mA and the maximum value is 1.6 mA at $V_{SA} = V_{SD} = 5$V without the bridge load. Thus the maximum quiescent power consumption is 8 mW. The dynamic power consumption actually equals to bridge strain transducer power consumption, about 6.381 mW mentioned in above section.

3.1.3. Lookup Table

Lookup table allows multi-slope compensation over temperature for nonlinear bridge strain transducer. Lookup table has access to 17 calibration points consisting of three adjustment values (Temperature, Zero DAC, Gain DAC) that are stored in 16-bit data format (17×3×16 = 816 bit). A 1k-bit EEPROM is enough when using all 17 temperature coefficients. Once power-up, the PGA309 resets the internal registers and then reads the configuration data from the external EEPROM device [22].

In our demonstration, 24LC01B is a 1 Kbit EEPROM from Microchip Technology Inc. This chip is organized as one block of 128 × 8-bit memory with a 2-wire serial interface. 24LC01B can operate at low voltages down to 1.7 V with low active (1 mA) and standby (1 μA) current, thus suitable for battery energy or restricted power applications. It has a two-wire serial interface which is used to communicate with the PGA309, and can also be used to interface with the MCU on the node. It is designed for more than 1 million erase/write cycles, and is also available in the 5-lead SOT-23 package. More details can be found in the datasheet [23].

3.1.4. Low Pass Filter

Since the aircraft structural element, such as the fuselage in flight, is also subjected to high frequency vibration, however, a relatively slowly varying quantity has been more interests in measuring strain. Thus the output of the PGA309 is fed to a low pass filter (LPF) to eliminate high frequency noise. Moreover, LPF may eliminate radio frequency interference (RFI) presented in the environment, it is especially important for a high-precision measurement device.

3.2. RF Transceiver and MCU

3.2.1. Low-Power RF Transceiver

An integrated RF transceiver solution (Fig. 4) may minimize device size and shorten the interrupt handling time. The CC2530 is a true system-on-chip (SOC) solution for IEEE 802.15.4 and ZigBee applications. The CC2530 combines inside the excellent performance of a RF transceiver with an industry-standard enhanced 8051 MCU, in-system programmable flash memory, 8-kB RAM, and many other powerful features. It provides extensive hardware support for frame handling, data buffering, burst transmissions, data encryption, data authentication, clear channel assessment, link quality indication and frame timing information, which can reduce largely the overhead of the processor [24]. Due to the low active power consumption, the standby power consumption and wide supply range, the CC2530 prolongs battery lifetime and reduces battery maintenance.

3.2.2. MCU

Wireless sensor nodes belong to embedded devices. Since a general-purpose microprocessor generally has higher power consumption than a microcontroller, it is often not considered a suitable choice for an embedded device. Digital signal processor (DSP) may be chosen for broadband wireless communication applications, but the WSN communication is often modest: simpler protocol, easier to handle modulation and the signal processing tasks on nodes are less complicated. Therefore the advantages of DSP are not usually of much importance to wireless sensor node. Field programmable gate array (FPGA) can be reprogrammed and reconfigured according to requirements, but this takes up more time and energy than desired. Therefore, the above processor architectures are almost infeasible for battery-powered wireless devices.

A microcontroller is often used in many embedded devices, because of its low cost, flexibility to connect, ease of programming, and low-power consumption. In our demonstration, the architecture option inclines to MSP430 microcontrollers, which is designed specifically for low-power operation. Depending on MSP430F2274 from the 2 Series MSP family, the current consumption of 0.7 μA during standby mode (LPM3) and 4.32 mA during active mode (AM) that make it an excellent choice for battery-powered applications. The power consumptions of main operating modes in MSP430F2274 will be shown in Fig. 9. MSP430 features a powerful 16-bit RISC CPU, 16-bit registers and constant generators that contribute to maximum code efficiency, from being the main applications and protocol process to coordinating communications [25]. In addition, an integrated 10-bit analog-to-digital converter supports conversion rates of up to 200 ksps that enough to complete sampling signal digitization for our demonstration.

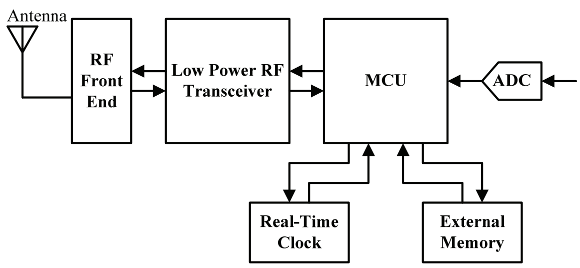

Fig. 4. Low-Power RF Transceiver and MCU.

3.3. Power Source

As shown in Fig. 5, power source module consists of an energy harvesting, a boost converter, energy storage and a smart switch in our demonstration. Energy harvesting resorts efforts to capturing ambient energy sources and transforms into electric power. Boost converter regulates and converts ultra-low level electric power into more usable level like a charger. Energy storage stores power generated from energy harvesting for later use. Energy storage may be an efficient quick charging capacitor or one of the newly developed thin film batteries. Generally, capacitor is used when the application needs to provide huge energy spikes. Battery is due to less current leakage and therefore used when the application needs to provide steady energy flows. The stored energy is triggered at the required condition to connect up power supply by a smart switch. All of these devices must be sufficiently robust to endure long-term exposure to hostile environments and have a broad range of dynamic sensitivity to exploit the entire energy spectrum. Moreover, extracting maximum power from energy harvestings places unique demands on the energy storage management architecture.

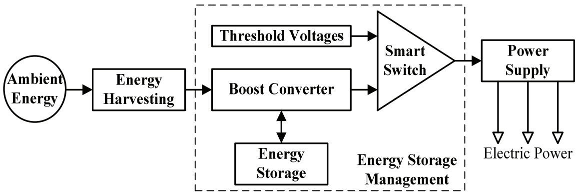

Fig. 5. Switch Mode Power Supply with Energy Storage Management and Energy Harvesting.

3.3.1. Energy Harvesting

Since the most wireless sensor nodes are powered from chemical batteries in the past, the schedule-based maintenance is needed. The battery lifetime is inherently limited so as to cause a maintenance problem [26]. Especially for a large-scale sensor networks, battery maintenances are inconvenient to implement, and also the battery reinforcements are infeasible to realize. Moreover, the growing demands of distributed computations and coordinating communications, such as the preprocessing and packaging of sensor data with the intent of minimizing wireless overhead to reduce power consumption and conserve network bandwidth, will result in such a rapid increase in the power usage of a wireless sensor. Energy harvesting can effectively provide a virtually perpetual energy source so that the battery does not require frequent maintenance [27].

Fig. 6 is a schematic diagram of the flexure element and proof mass. The piezoelectric (PZT) materials are utilized to convert vibration energy into electric power. It is comprised of a tapered flexure element with PZT mounted on the top and bottom of a cantilever beam. The tapered cantilever structure is designed to create a nearly uniform strain field on the PZT elements. A proof mass is affixed to the end of the beam, which resonated at a specific frequency. Such equipments capture vibration energy for powering wireless sensor nodes that have been reported [28]. Other researchers have been active in this area as well, and have described various strategies for harvesting, or scavenging energy from the environment, such as thermoelectric harvesting, photovoltaic harvesting, RF harvesting, etc [27].

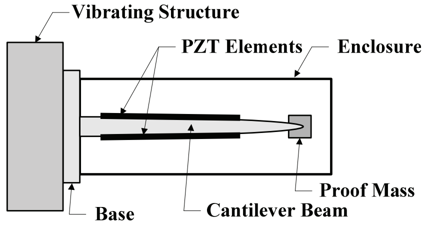

Fig. 6. Piezoelectric Vibration Energy Harvesting Cantilever Flexure Element with Proof Mass.

3.3.2. Energy Storage Management

Although the current energy harvesting technology offers the significant advantages over WSN, the availability of the energy source is often sporadic or time-varying so that an energy storage element is typically needed. The energy storage element can provide certain constant power and allow the device to handle any peak currents that can not directly come from energy harvesting. To prevent energy storage element from damaging, the output voltage of boost converter is compared against the pre-set battery threshold by a smart nanoampere comparator switch (see Fig. 5). This switch features very low closing resistance and very high switching frequency. Such a configuration is very critical for aircraft flight condition where the ambient energy levels may be low or intermittent. Without this switch, the device may never successfully start up, because stored energy levels may always remain insufficient for the task at hand.

Fig. 7 shows the key threshold voltages and operation states that are programmed independently for successfully harvesting ambient energy source and protecting energy storage element. When the input voltage coming from energy harvesting exceeds the minimum input voltage with sufficient power, the cold start state turns on the device to initiate boost converter. After the output voltage continues to increase and keep in pre-set time, cold start state is turned off and the energy storage element starts to charge up. To prevent rechargeable batteries from being deeply discharged and damaged, or to prevent a capacitive storage element from being completely depleting charge, the under voltage threshold must be set to disconnect battery powered. To prevent rechargeable batteries from being exposed to excessive charging voltages, or to prevent a capacitive storage element from being over charging, the over voltage threshold must be set to step down the charging voltage or disable battery charging. An acceptable battery good threshold must be set to instruct work under normal conditions. To avoid misuse and erroneous act due to ripple voltage, the respective hysteresis voltage thresholds should also be reasonable to set.

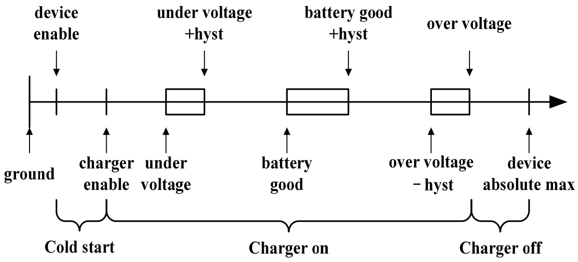

Fig. 7. The Relevant Location of Key Threshold Voltages and Operation States.

The bq25504 and its corresponding external circuit can be designed to efficiently acquire and manage power generated from energy harvesting. The bq25504 integrates a highly efficient boost converter that requires only microwatts of power to begin operating, especially for WSN which has stringent power and operating demands [29].

4. System-level Energy Management

The trade-off between the low-power consumption and high processing speed is a key design for embedded devices. On the one hand, the battery capacity has improved very slowly. But on the other hand, the wireless communication and local computation have drastically increased over the same time frame. Therefore, the development of wireless sensor nodes has stressed even more the needs of the energy minimization. Due to the fact that the wireless nodes are energy constrained even if joining with an energy harvesting, power consumption must be minimized reasonably and managed effectively. A better low-power hardware design technique has helped to lower the power consumption. On the other hand, managing power consumption at higher system-levels can considerably decrease energy requirements, and thus prolong battery lifetime, lower packaging and cooling costs [30]. Two different approaches for lowering the power consumption at the system level have been proposed: dynamic voltage scaling (DVS) and system-level dynamic power management (DPM).

4.1. Dynamic Voltage Scaling

One approach of lowering the power consumption is to slow down the execution or disable some functions and features, when appropriate, also lower the operating voltage of the component. Fig. 8 shows that MSP430 MCU operates at the workable processor frequency corresponding to the supply voltage. Processor frequency is defined by supply voltage. Flash program or erase operations require a minimum V_{CC} of 2.2 V [25].

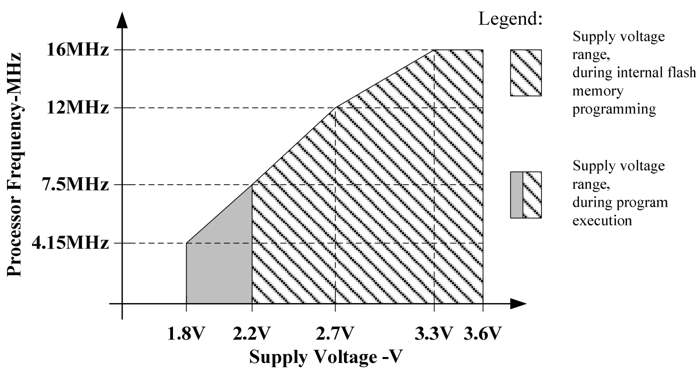

Fig. 8. Operating Area of MSP430 MCU.

4.2. Dynamic Power Management

Embedded sensor devices are designed to be able to deliver peak performance when needed, but their components execute at utilizations less than 100% over the most time. In contrast to DVS, DPM decreases the energy consumption by selectively placing idle components into lower power states. In fact, the wireless communications consume a large fraction of the overall energy consumption in most current wireless sensor nodes. Fig 9 shows a power consumption breakdown for our demonstration. In the same power supply rail, the wireless communication takes up above 90 % of the overall power budget and the second power hungry device is the MCU. Therefore, the optimization of both computing and communication energy consumption is critically important to achieve long battery lifetime.

DVS can only be applied to MCU, while DPM can be applied to RF transceiver, MCU, and all other components that have low-power states. The two approaches are combined effectively in our demonstration.

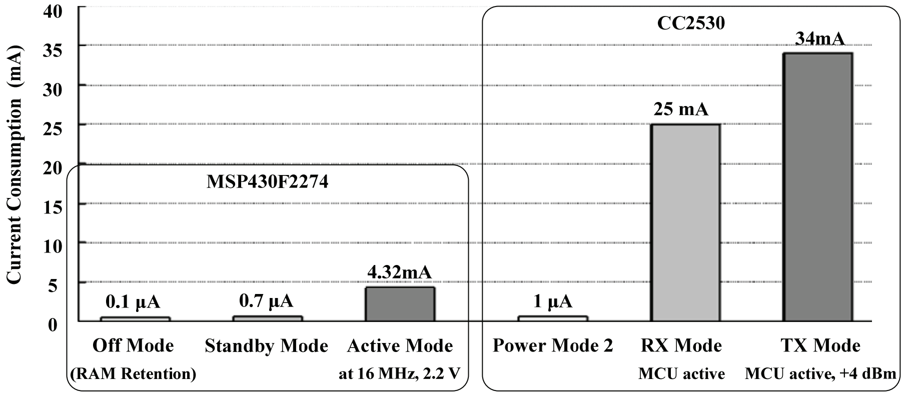

Fig. 9. Power consumption of the two main power hungry components in our sensor node demonstration without counting the external circuit consumption.

4.3. Critical Event-Triggered Transmission

Besides the selection of the low-power components in hardware, system-level energy management design is also needed to consider further. In most cases, the sensor signal swings within a range and then restores stability in the new status phase for some time. The real-time transmission of sensor data needs to consume energy and occupy bandwidth. An autonomous wireless sensor node can adequately observe the dynamics of monitored object and also perform suitable signal processing and feature extraction. Bandwidth is an important resource as well as energy in the scale WSN. A universal solution towards decreasing power consumption is to employ periodic wake-up scheduling, where nodes stay in low-power or sleep modes for the most time that has been described in many literatures [31, 32], however, this method will possibly cause the loss of critical data and signal delay resulting in a deteriorate online monitoring.

Fig. 10 shows the conversion workflow of critical event-triggered transmission scheme between the two working modes applied in our demonstration. In contrast with the periodic wake-up scheduling, our scheme is a good way to reasonably reduce power consumption and conserve network bandwidth. When the variation range of acquired sensor data does not exceed the comparison threshold based on a predetermined initial value, normal mode turns on the device to storage temporarily sensor data into the external flash memory, set sampling rate at 32 Hz, perform timing synchronization and upload data packet to data aggregator once every 60 s. Hence, the maximum value of data delay is theoretically 60 s for remote monitoring side.

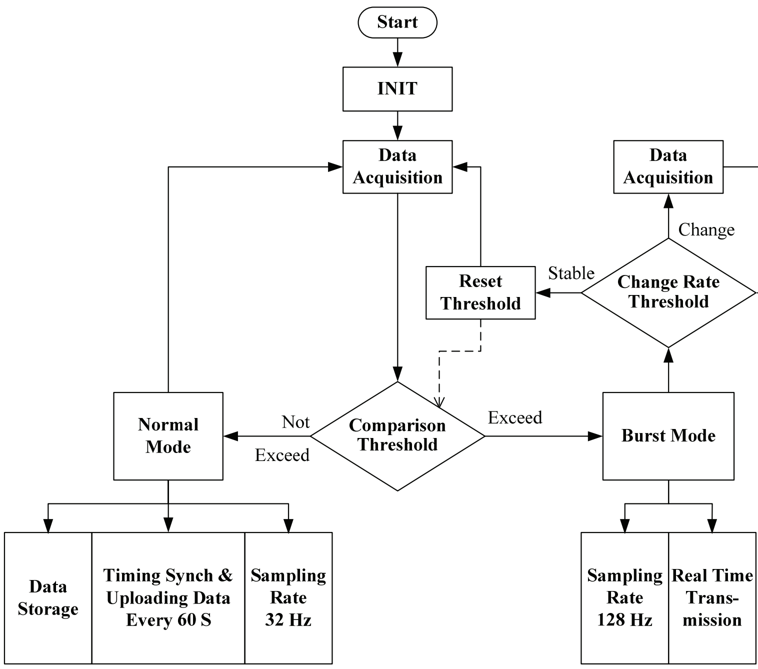

Fig. 10. Critical Event-Triggered Transmission Scheme Workflow Chart.

Additionally, the RF part (CC2530) can even sleep for most of the time, ignore most broadcasts from the network and only needs to periodically wake up to perform timing synchronization to conserve energy. It is worth noting that timing synchronization is a critical piece of infrastructure for any distributed system, especially for WSN. Although each node contains a real-time clock, environmental temperature differences, parameter error and cumulative error will lead to timing drift among network, which can be corrected by a centrally broadcast synchronization beacon. A good algorithm for the compensation of the timing drift is inevitable to achieve high precision and low communication overhead.

When the variation range of sensor data exceeds the comparison threshold and keeps in pre-set time, the node performs the transition from normal mode to burst mode, the sampling rate is set up to 128 Hz and the real-time transmission is perform to track the monitored object. If the change rate of sensor data is greater than zero, the node still sticks in burst mode. Once the change rate is stable within a permissible minimal range for some time, the node returns to normal mode and resets a new comparison threshold based on current stable value.

Fig. 11 shows that our aircraft SHM system can monitor synchronously the structures on GPS, inertia, pressure, acceleration, temperature, humidity, and illumination data via a range of wireless sensors cooperated with some hard-wired sensors.

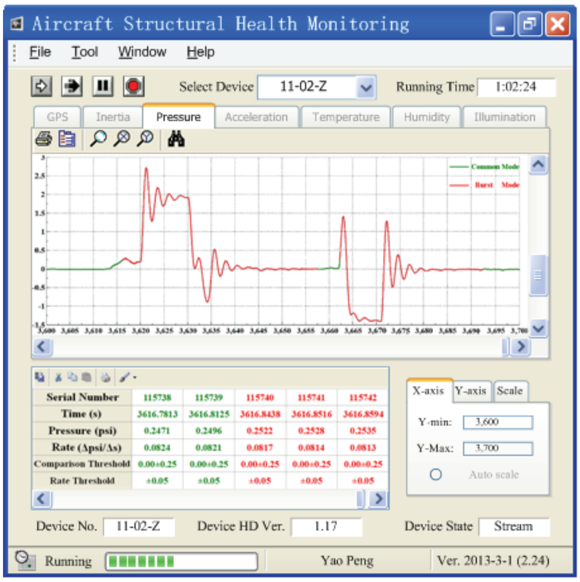

Fig. 11. Human-Machine Interactive Interface of Aircraft Structural Health Monitoring System.

As shown in Table 2, the sensor data of a critical event example can be obtained to illustrate the transition from normal mode to burst mode. Before the 3616.8125 s, the green mark is used to indicate that the node works in the normal mode, i.e. demands for data acquisition at the interval of 1/32 s. At the 3616.8438 s, since the pressure data is 0.2522 psi that exceeds the current given comparison threshold of ± 0.25, the node transits to the burst mode, i.e. demands for data acquisition at the interval of 1/128 s and upload data in real-time. The red mark is used to indicate that the node works in the burst mode.

Table 2. Transition from Normal Mode to Burst Mode (screenshot from aircraft SHM system).

Serial Number	115738	115739	115740	115741	115742
Time (s)	3616.7813	3616.8125	3616.8438	3616.8516	3616.8594
Pressure (psi)	0.2471	0.2496	0.2522	0.2528	0.2535
Rate (Δpsi/Δs)	0.0824	0.0821	0.0817	0.0814	0.0813
Comparison Threshold	0.00±0.25	0.00±0.25	0.00±0.25	0.00±0.25	0.00±0.25
Rate Threshold	±0.05	±0.05	±0.05	±0.05	±0.05

As shown in Table 3, after the 3683 s (not shown in the Table 3), since the change rate consistently lowers than the rate threshold value of ± 0.05, and the preset stable time is set for 10 s, therefore, at the 3693 s, the node transits back to the normal mode. Meanwhile, according to the approximation of current data value, the node resets the comparison threshold value from 0.01 ± 0.25 to − 0.01± 0.25.

Table 3. Transition from Burst Mode to Normal Mode (screenshot from aircraft SHM system).

Serial Number	125897	125898	125899	125900
Time (s)	3692.9922	3693	3693.0313	3693.0625
Pressure (psi)	−0.0096	−0.0095	−0.0090	−0.0085
Rate (Δpsi/Δs)	0.0176	0.0173	0.0165	0.0151
Comparison Threshold	0.01±0.25	0.01±0.25	−0.01±0.25	−0.01±0.25
Rate Threshold	±0.05	±0.05	±0.05	±0.05

5. Conclusions

Despite the limitations of the current prototype, the overall results presented by the experimental tests are satisfactory. Nevertheless, further tests are needed to perform in order to assess the behaviors of the system under more harsh conditions. In real scenario of onboard aircraft, the system design will be much more complicated and sophisticated because of the enhanced efficiency and reliability by a greater number of monitoring points to be measured. Furthermore, The SHM of a full-scale aircraft requires the higher demands of transmission rate, timing synchronization, data processing capacity and so on. Therefore, there are some significant technical challenges for the successful implementation of aircraft SHM.

The WSN represents an exciting development, with the potential to integrate into an aircraft environment for SHM applications. The combination of advanced technologies including WSN, low-power design, system-level energy management, energy harvesting, signal acquisition and data processing, etc is a powerful solution for SHM. These capabilities coupled with the appropriate methods will enable critical structure to be monitored remotely, securely and automatically. Our future research and work should be directed in addressing the below technical challenges: The SHM system is capable of transmitting monitoring results via satellite. The area of information fusion between wireless network and hard-wired network (or bus) is conducted. A new wireless aircraft certification regulation needs to be developed to prevent the various security and safety threats.

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